



Buckling of a Longitudinally Jointed Curved Composite Panel Arc Segment for Next Generation of Composite Heavy Lift Launch Vehicles: Verification Testing and Analysis

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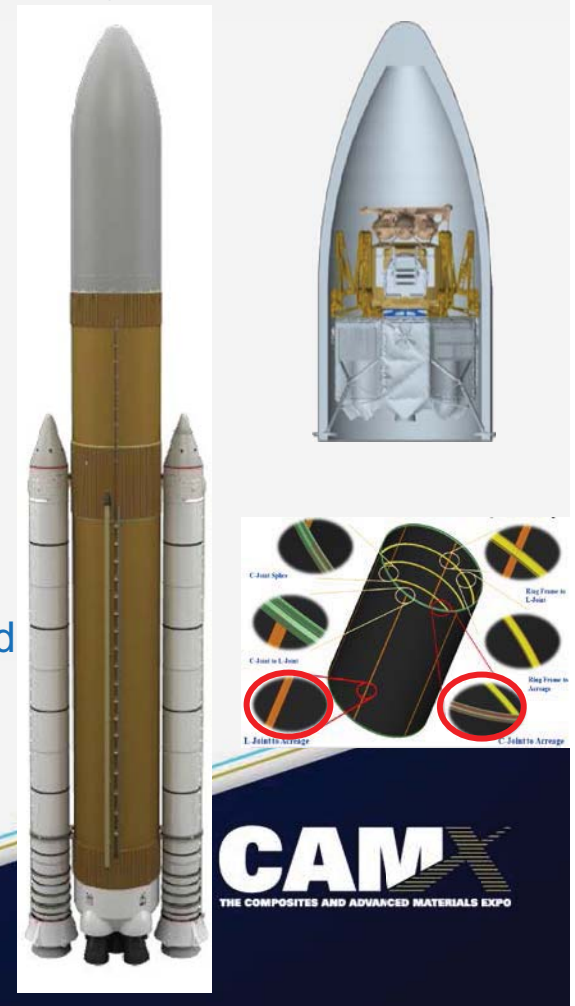


Overview

The objective of this work was to exercise an out-of-autoclave all-bonded joint design concept for a Space Launch System (SLS) fairing during the Composites for Exploration (CoEx) effort

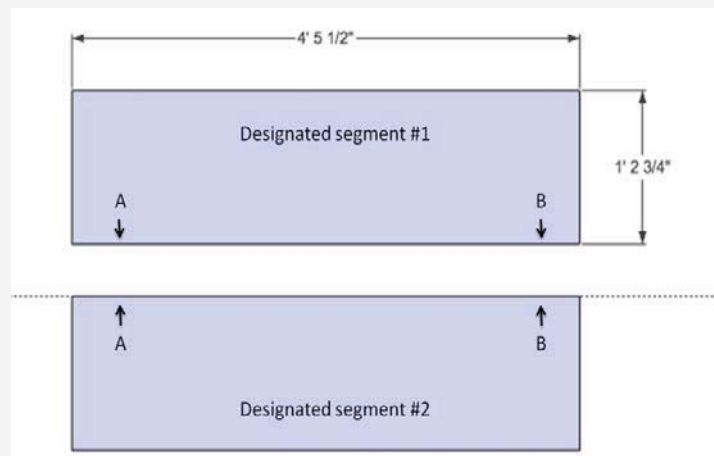
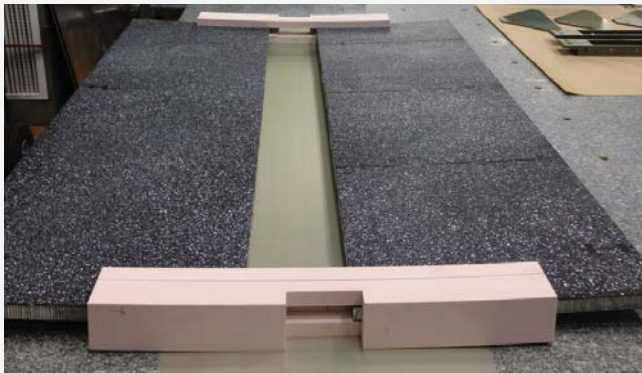
This presentation aims to:

- Report the buckling test and analysis correlation results for the 54" x 29" CoEx IM7/977-3 jointed panel. The analyses include:
 - Pre-test analyses to obtain a baseline buckling load and the stress state
 - A trade study to look at design changes to lower the panel ends/corners stresses
 - Correlating the buckling test data:
 - Using linear vs. non-linear analysis
 - Investigating surface (shape) imperfections on the jointed panel buckling behavior
- Present a summary results of the damaged jointed panel buckling and edge-supported compression tests, and to discuss the next steps to correlate the observed behaviors

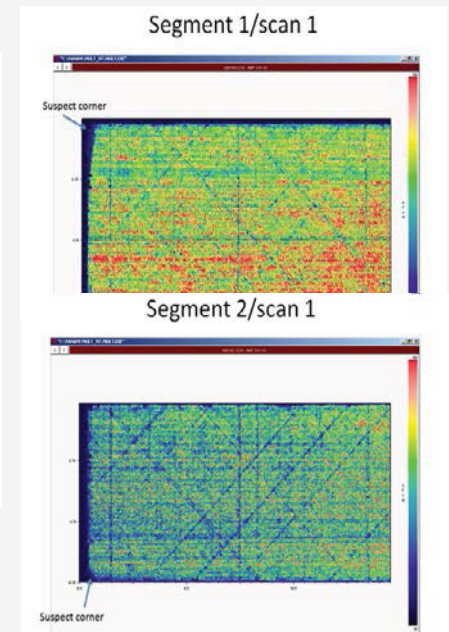


Background

- The parent material:
 - The Hitco demonstration HC sandwich panel, 1/16th arc segment of 33-ft diameter cylinder, made under the CoEx program
 - 8-ply $[45^\circ/90^\circ/-45^\circ/0^\circ]_s$ face-sheets (IM7/977-3) with 1 in thick 3.1 pcf Al honeycomb core



Note: The final trimming reduced the overall size of the “jointed panel” to 52 in. x 27.8 in. (The panel still to be referred to as 54 in x 29 in)



Bonded Joint Configuration

--- Top of Layup ---

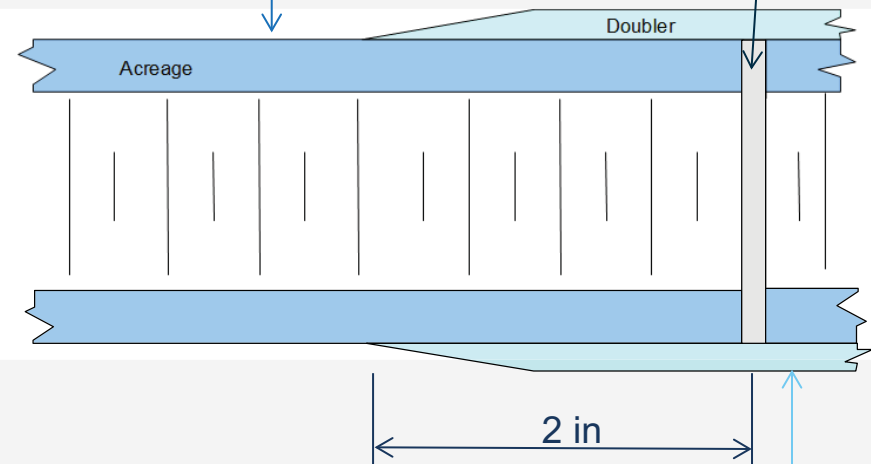
Total Thickness = 0.0424

Ply ID	Global Ply	Material	Thickness	Angle
8		3..IM7-977-3	0.0053	45.
7		3..IM7-977-3	0.0053	90.
6		3..IM7-977-3	0.0053	-45.
5		3..IM7-977-3	0.0053	0.
4		3..IM7-977-3	0.0053	0.
3		3..IM7-977-3	0.0053	-45.
2		3..IM7-977-3	0.0053	90.
1		3..IM7-977-3	0.0053	45.

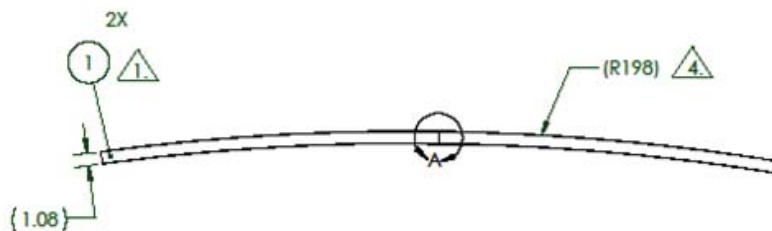
--- Bottom of Layup ---

IM7/977-3

Potting compound
0.1" Max. width



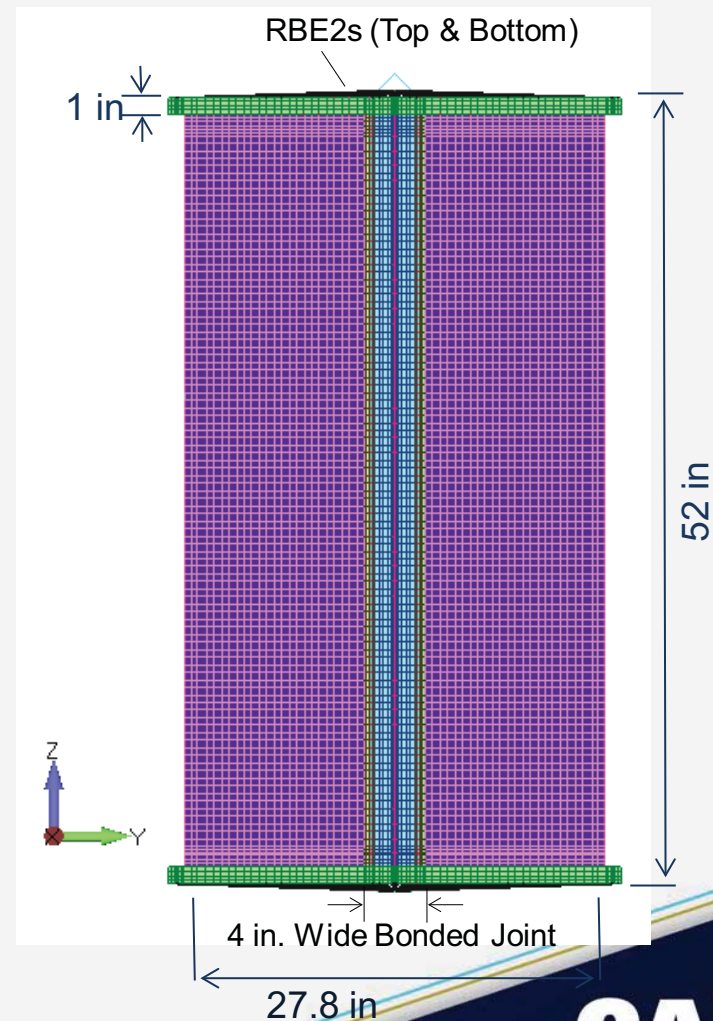
5-ply out of autoclave cured plain weave
(T40-800/5320-1) laminate



- Cured ply thickness: 0.008 in
- Dominant mechanical properties were obtained through testing
- Joint out-of-autoclave cured to H/C panel in a co-bond operation
- The joint was made and inspected without any flaws

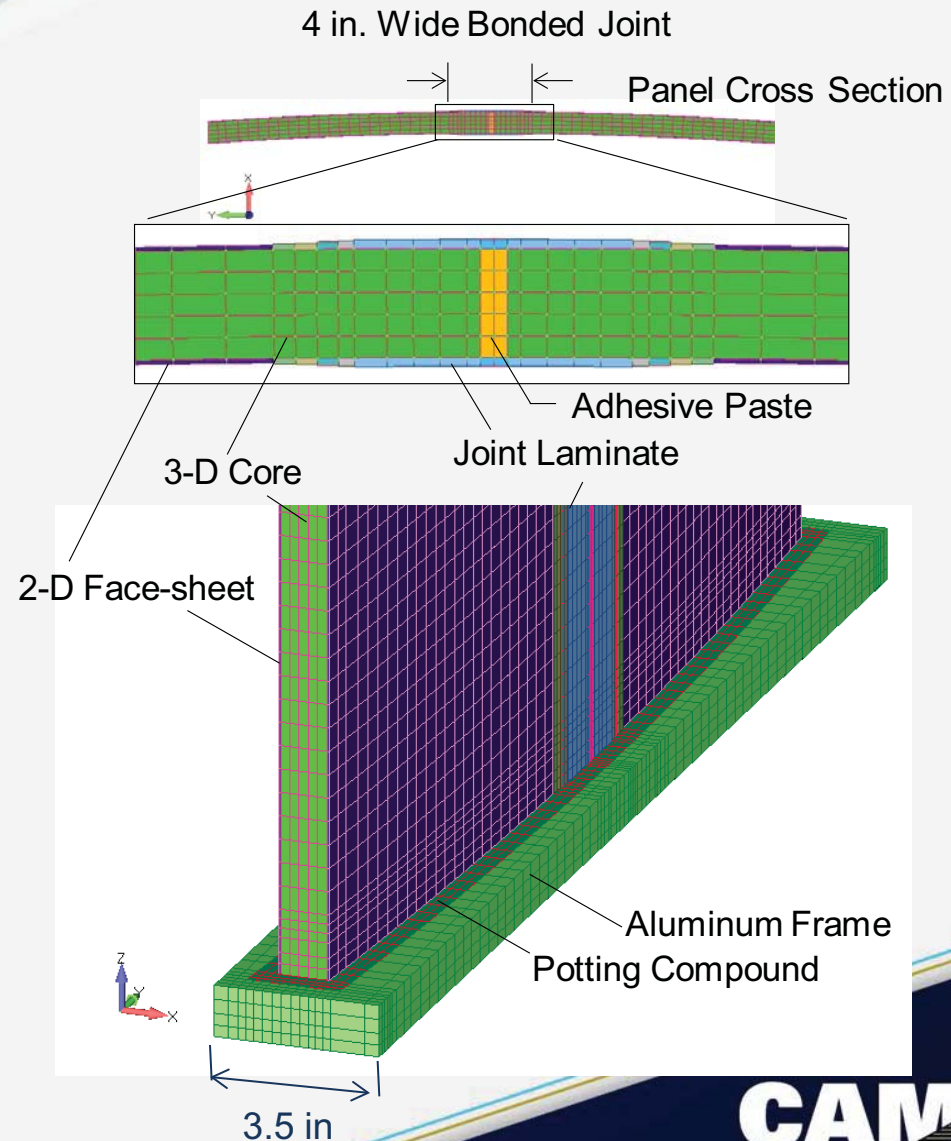
The Baseline FE Model Description

- ~0.5-in. element size with finer mesh at the joint region and at the fixed ends
 - Total of 61,146 elements and 56,444 nodes
- Face-sheets and bonded joint were modeled using 2-D elements (CQUAD4/PCOMP) with proper off-setting
- RBE2s were used to apply load and boundary conditions at the top and bottom
 - Top: Applied nodal load/displacement while constraining all degrees of freedom except for the axial translation
 - Bottom: Fixed



The Baseline FE Model Description – Cont.

- Core was modeled using solid elements (5 elements through the thickness)
 - 2-D plate elements share nodes with the most inner/outer core solid elements
- Potting region and the Al frame (fixture) were modeled using solid elements
- Cut (potting) was modeled ~0.24 in wide to avoid a very fine mesh

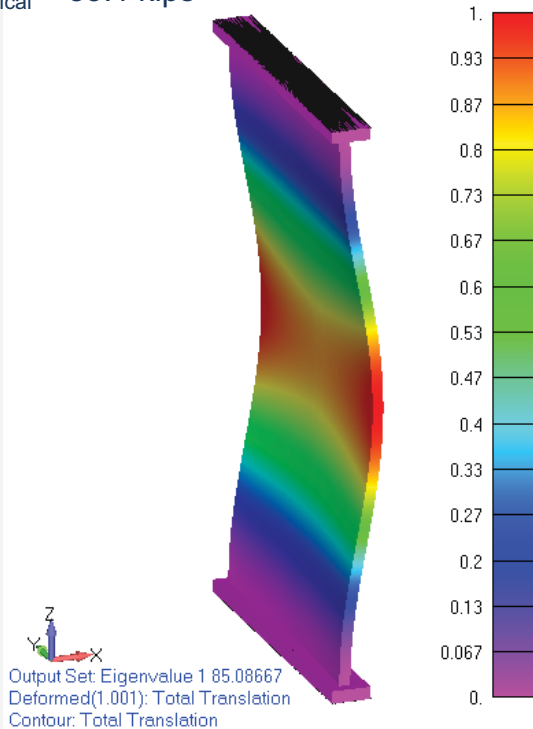


Buckling and Strength Baseline Analyses

NASTRAN linear SOL 105

Euler eigenvector buckling contour

$P_{critical} = 85.1$ kips



Hexcel Core Stress Allowables:

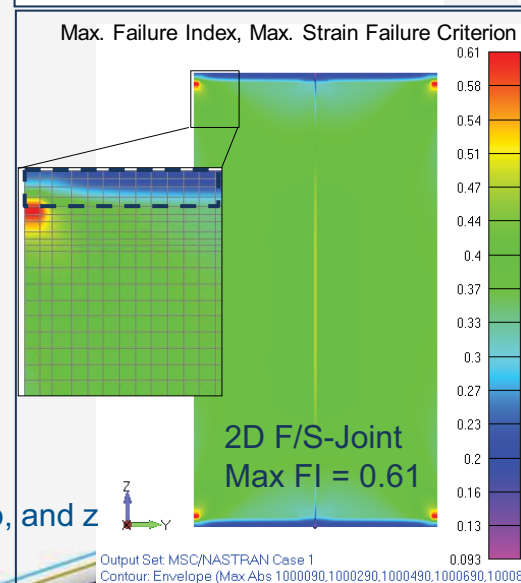
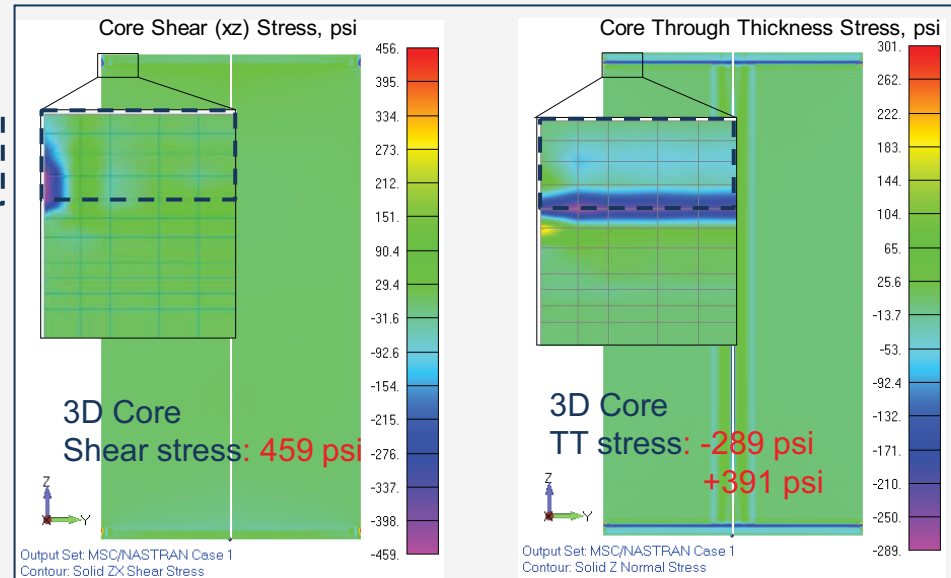
Shear (xz): ~145 psi

Compressive stabilized strength:

215 (min) - 300 (typ) psi

Crush strength: 130 psi

Note: For stress components: x indicates axial, y hoop, and z through thickness directions.



Strength (SOL 101):

- Stress concentration in F/S and core at ends/corners
- FI = 1 indicates failure

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Panel End-Condition Improvement

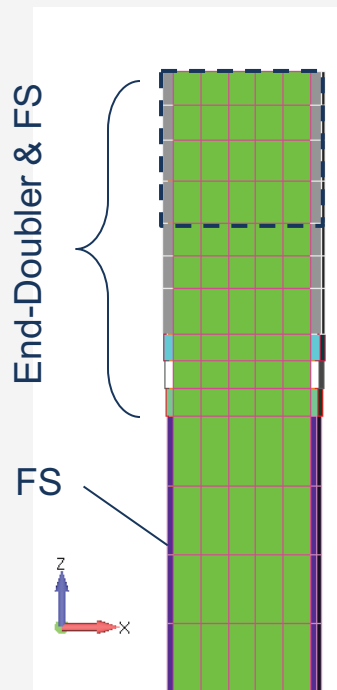
To address the high stress concentration issue at the ends/corners the following modifications were examined:

- Adding doublers to panel ends
- Including stress relief features into the potting compound
- Having both, the end-doublers, and the stress relief features

Adding End Doublers

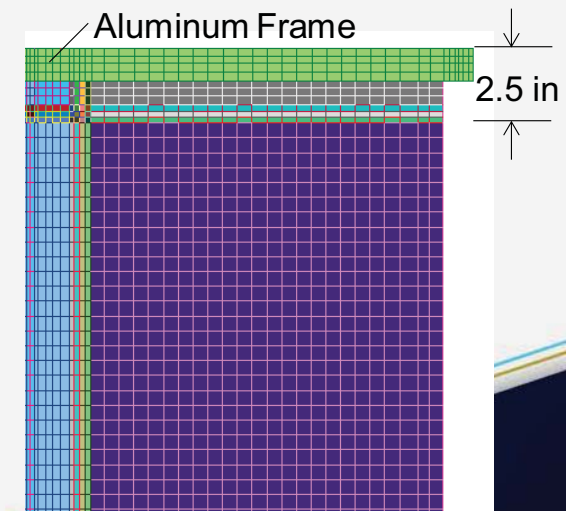
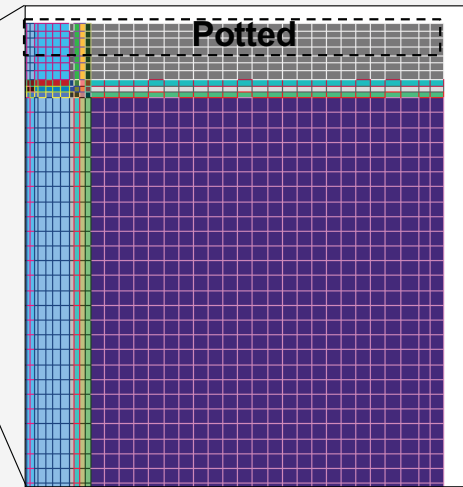
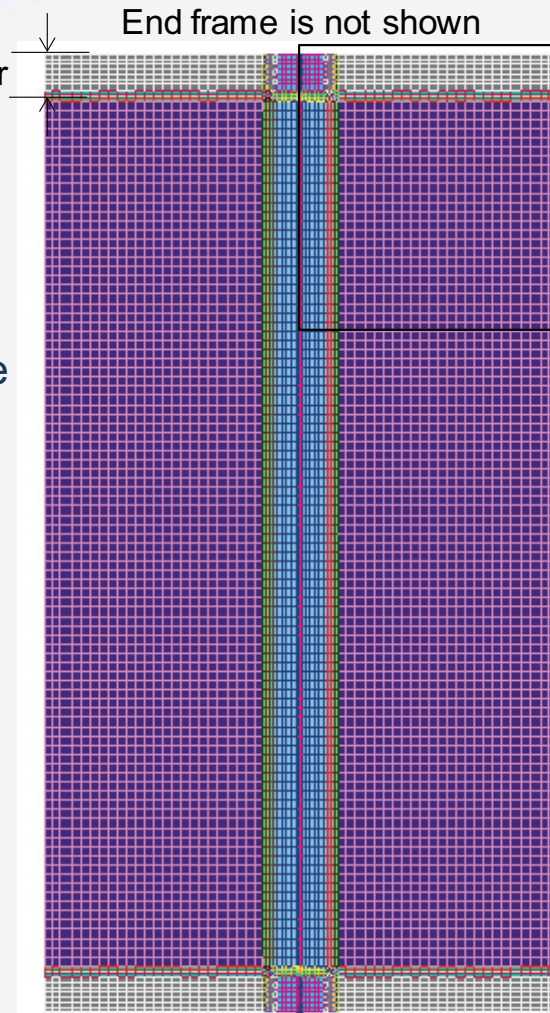
Doublers

- Plain weave
- A 4-ply laminate
- Co-bonded to panel at same time as joints



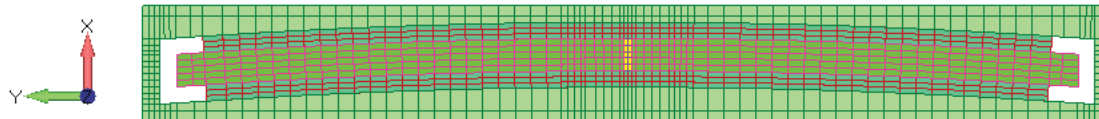
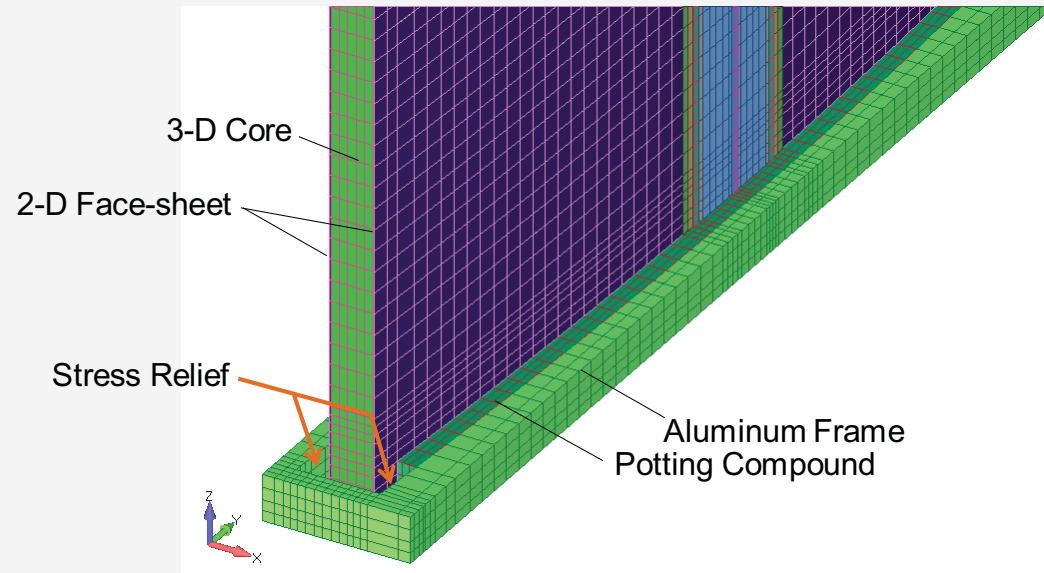
2.5 in Wide Doubler

End frame is not shown



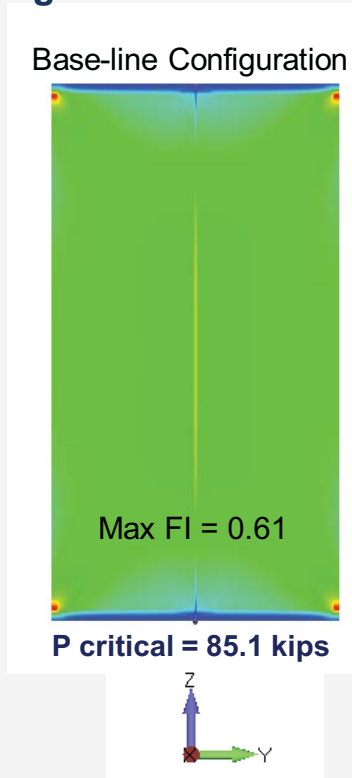
Adding Stress Relief Features

- The potting compound at the corners was removed, as shown, to release the stresses at the corners/edges



Face-sheet/Joint/Doubler Failure Index

Failure Index Contour
(Max. Strain Failure Criterion)
at the critical buckling load, for
each configuration

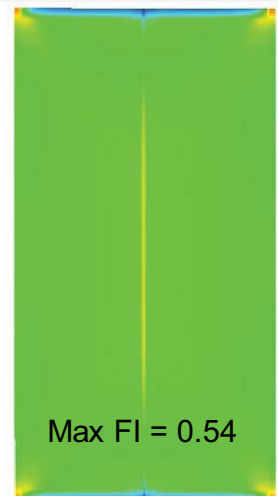


with End-doublers (only)

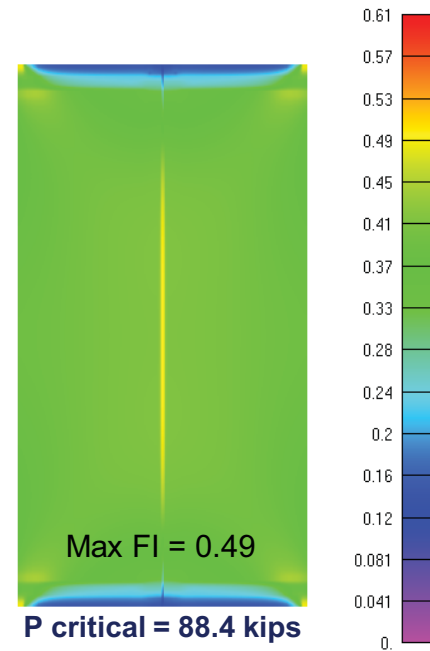


P critical = 88.7 kips

with Stress Relief Features (only)



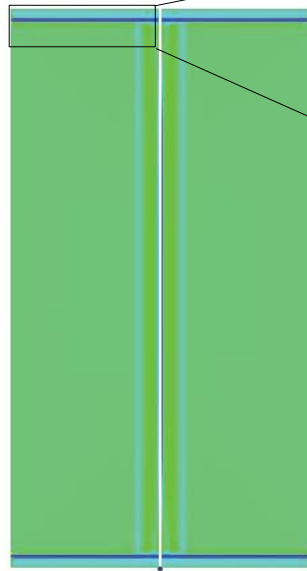
Failure Index Contour, Max. Strain Failure Criterion
with End-doublers and Stress Relief Features



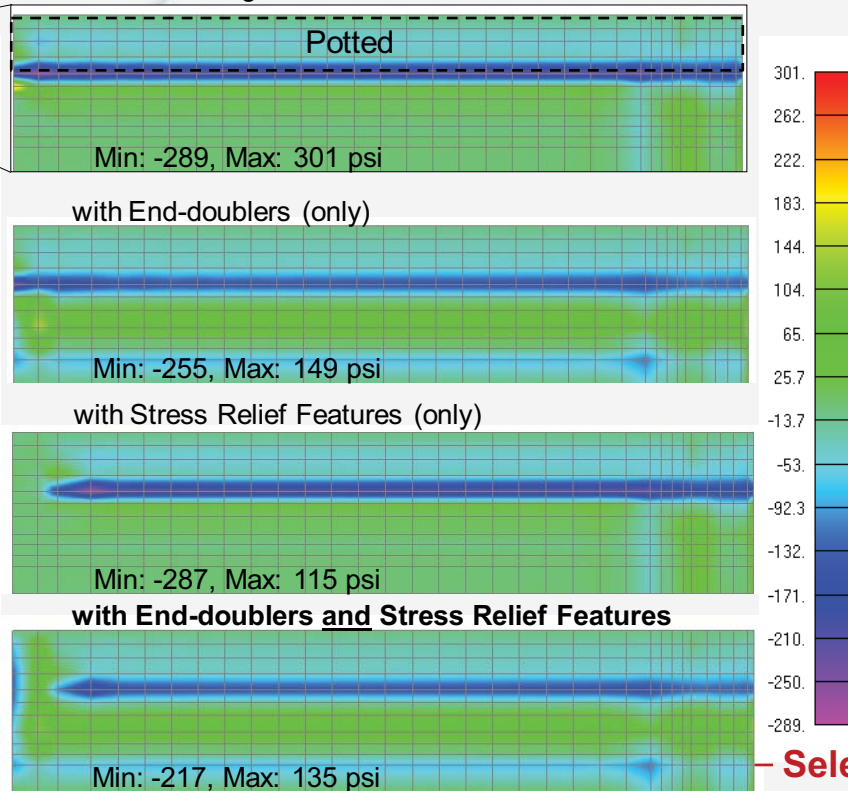
Selected Design

Core Stresses

Base-line Configuration



Core Through Thickness Stress at Panel Ends, psi
Base-line Configuration



← **P critical = 85.1 kips**

← **P critical = 88.7 kips**

← **P critical = 84.9 kips**

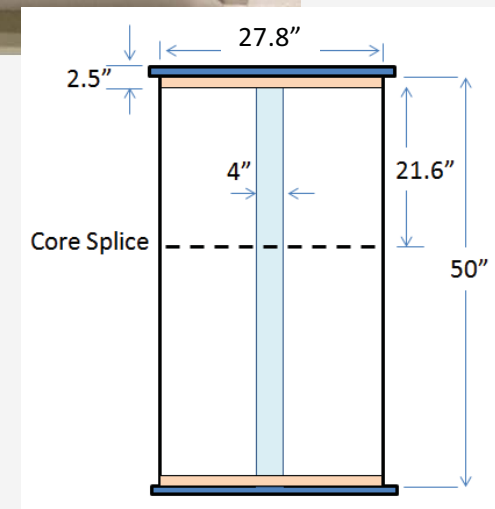
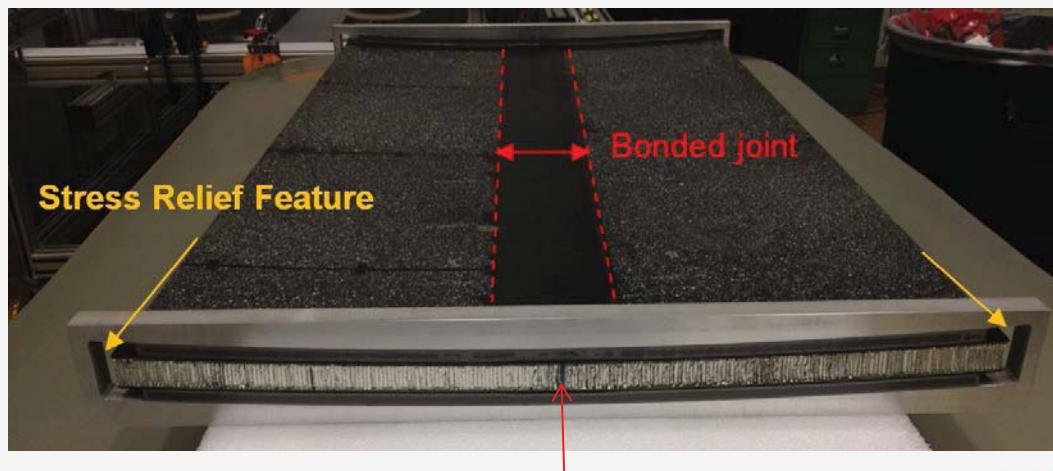
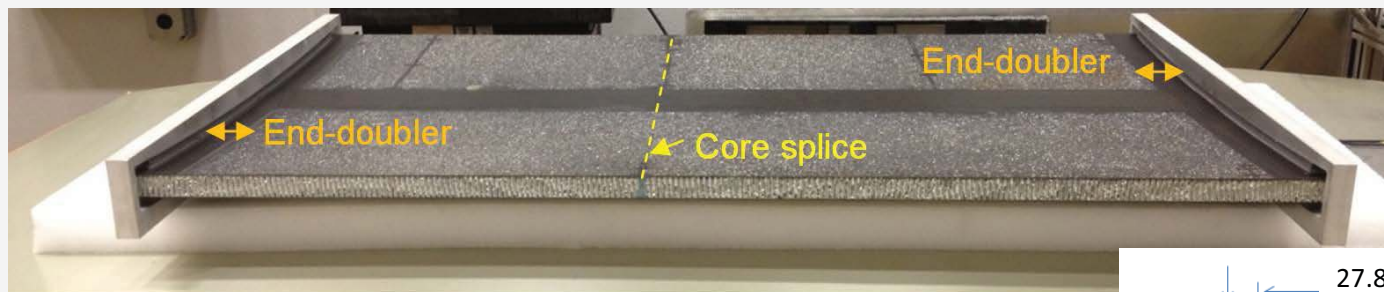
← **P critical = 88.4 kips**

← **Selected configuration**

Configuration	SOL 105 Buckling Critical Load (kips)	Face-Sheet and Joint	Honeycomb Out-of-Plane Stresses, psi		
		Max. FI	Min σ_z	Max σ_z	$ \tau_{zx} $
Base-line	85.1	0.61	-289	301	459
with End-doublers	88.7	0.50	-255	149	478
with Stress Relief Features	84.9	0.54	-287	115	101
with End-doublers and Stress Relief Features	88.4	0.49	-217	135	75

Test Article

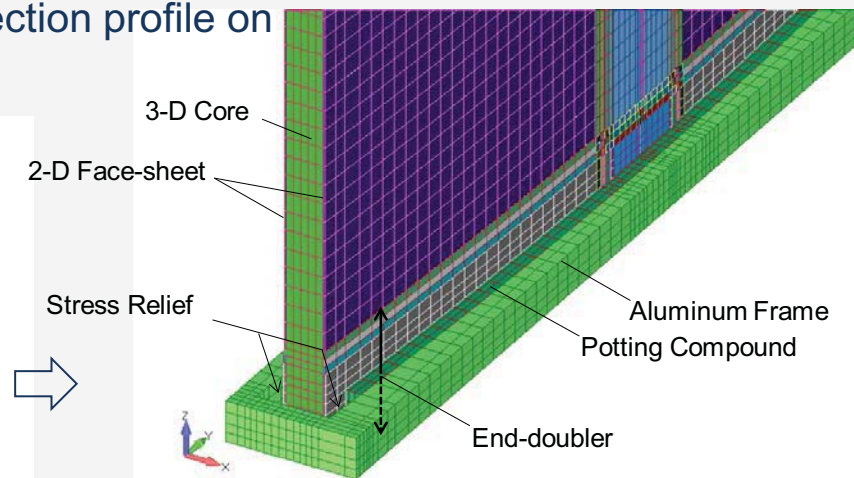
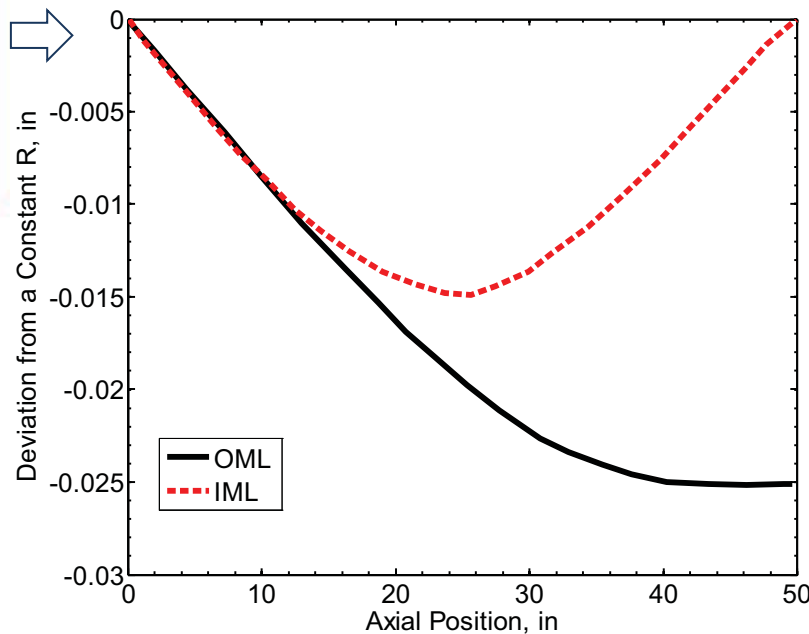
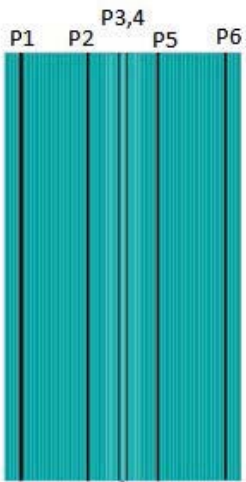
- Made to the recommended specifications
- The joint was inspected without any flaws (Also, made NDE standard)



Joint Seam

Surface Non-uniformities to FE Model

- Prior to testing, surface imperfections were measured on both the IML and OML surfaces, individually
- Used single feature point inspection to create point clouds on both the IML and OML surfaces
- The point clouds were then traced along the length of the panel at six different width locations (two on each left, center and right sides) to obtain an imperfection profile on each surface

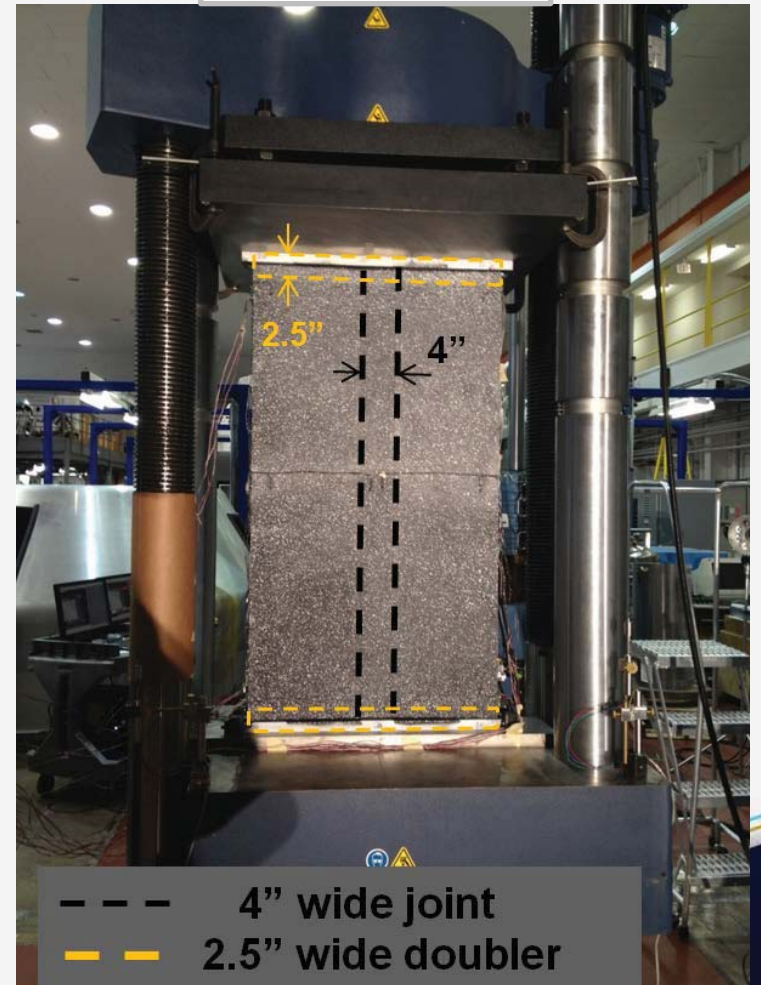


- An estimate of the worst case profile with the maximum bow magnitude was incorporated into the FE model for FE analysis

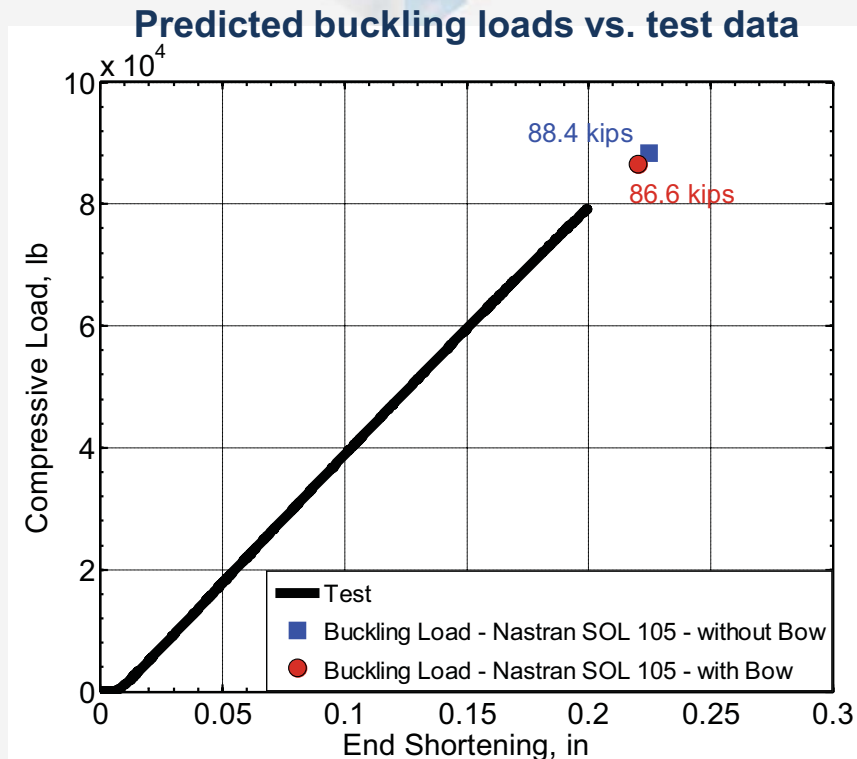
Buckling Test

Buckling Test # 1

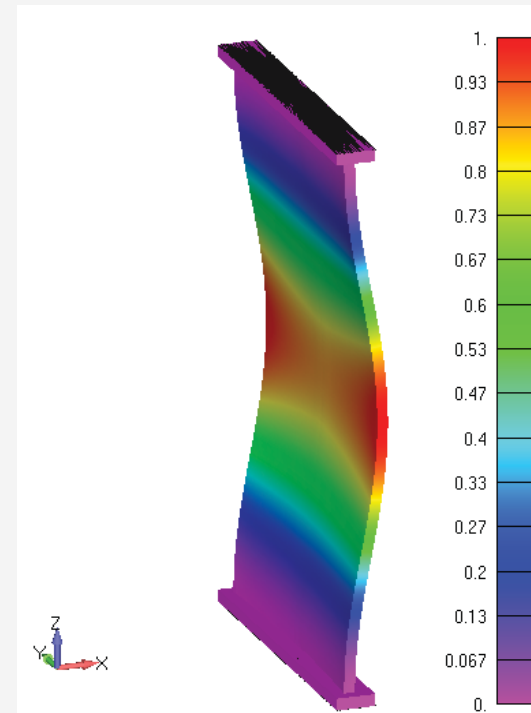
- Test was Conducted (by S. Kellas) at LaRC
- The jointed panel reached buckling load of 79.3 K-pounds without joint failure
 - Panel buckled toward IML
- Test Details:
 - 600-kip test frame
 - Photogrammetry (VIC system) on both surfaces to obtain full-field strains/displacements
 - Four displacement transducers to measure end shortening
 - Total of 20 back-to-back strain gages on OML/IML for local strain measurements, specimen alignment and controlling the test



Surface Imperfection Affected Linear Buckling Response



- ~11% over predicting the buckling load when surface imperfections are not included
- ~8% over predicting when the surface imperfections are included
- ~4% difference in stiffness between test and analysis

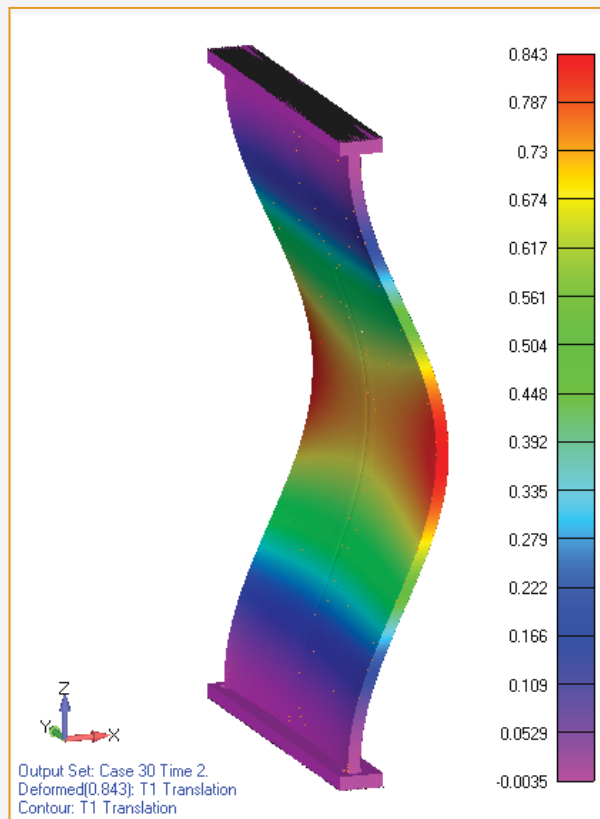


NASTRAN linear SOL 105 Euler eigenvector buckling contour

Surface Imperfection Affected Non-linear Buckling Response

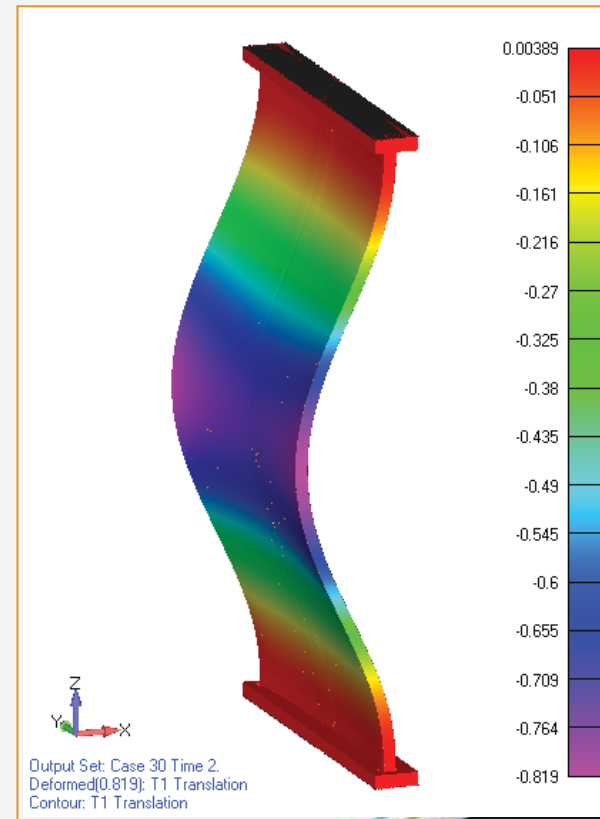
- Out-of-plane deformation at 0.25" imposed axial displacement

Surface imperfection NOT included in FEM



Panel buckles towards OML

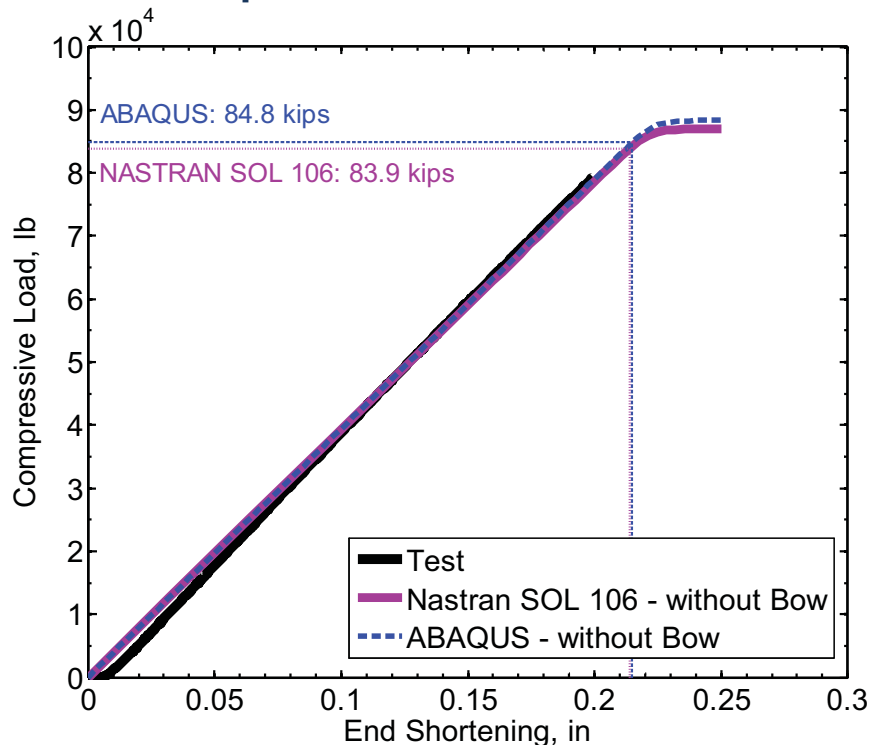
Surface imperfection included in FEM



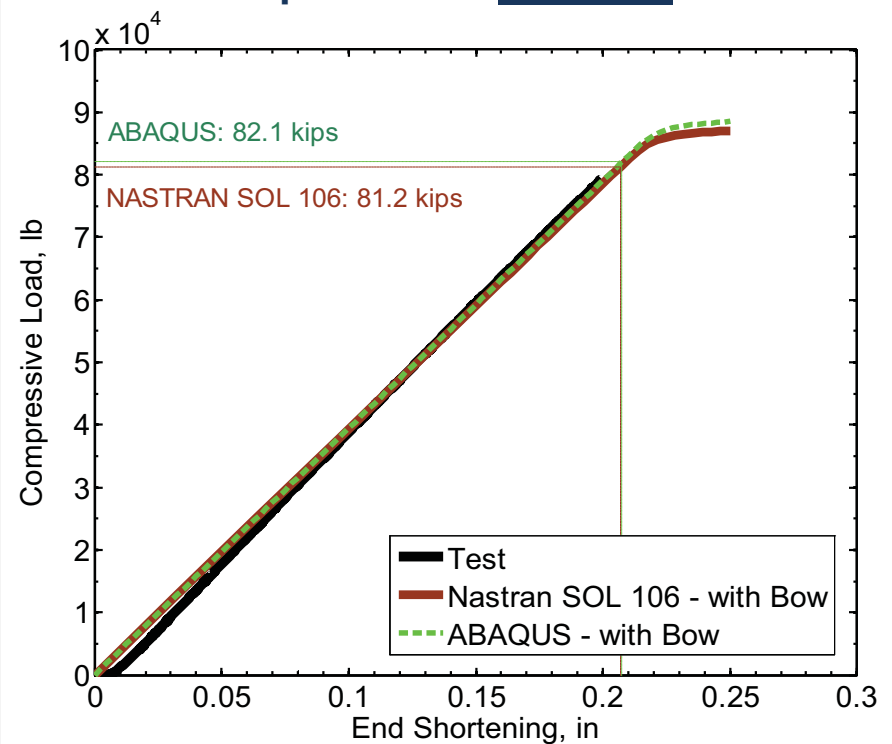
Panel buckles towards IML
Consistent with experimental observation

Bow Affected Buckling Critical Load

Surface imperfection NOT included in FEM

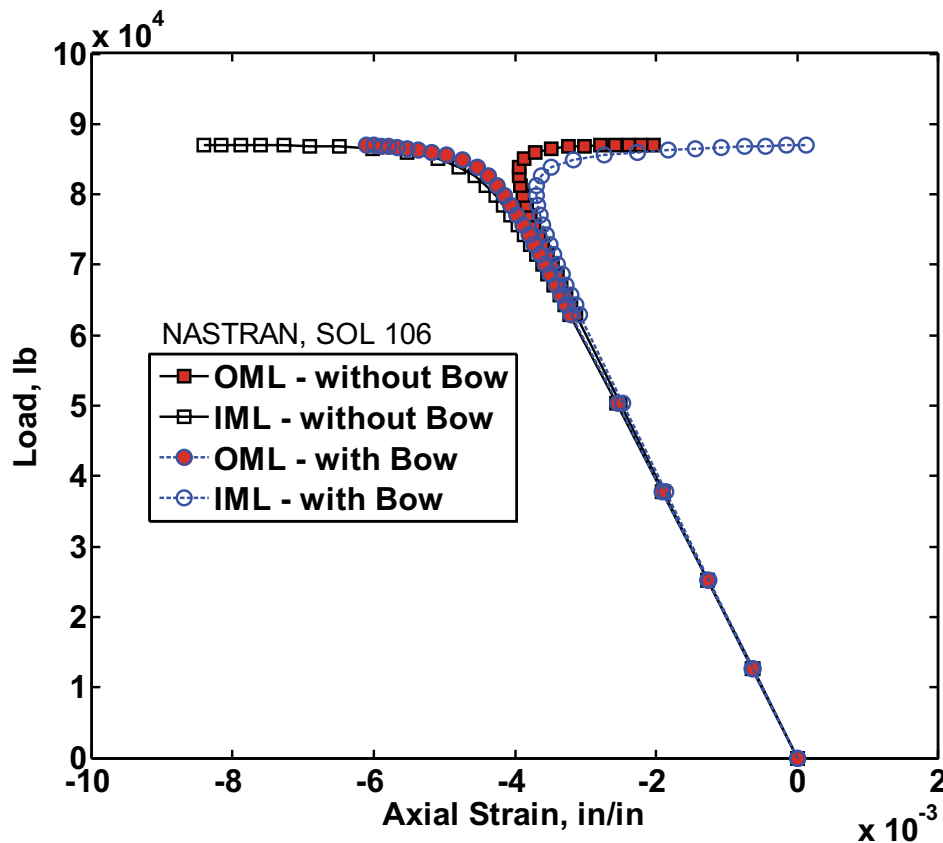


Surface imperfection included in FEM

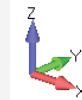


- Critical buckling load decreases as a result of including the surface Imperfections
 - From within 5% the test value to about 2%

Onset of Buckling Determination



Back-to-back
2D elements



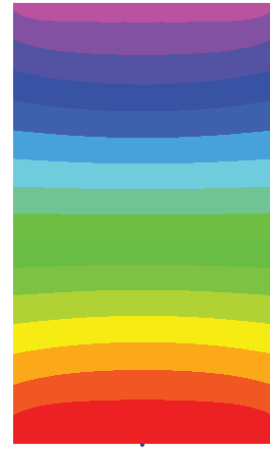
Monitoring back to back elements' axial strains, in the panel's middle edge to determine the onset of buckling analytically – Analogous to what determines when the buckling event has occurred during the experiment, prior to unloading the panel, without cartographically failing the specimen.

Axial Deformation/ End Shortening Correlation

Test correlation at buckling load of ~79.3 kips

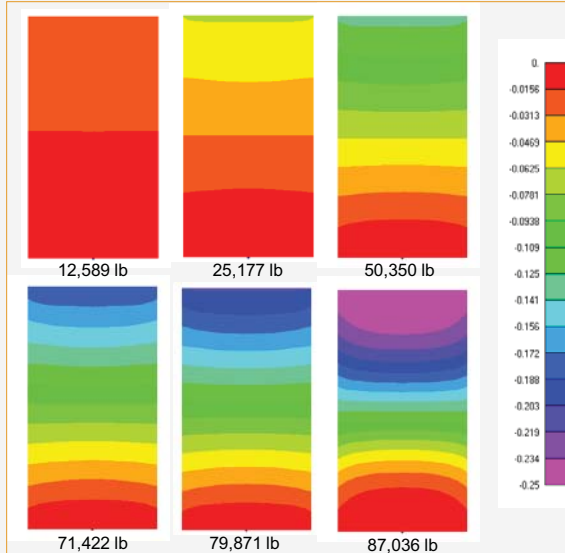


OML VIC Results

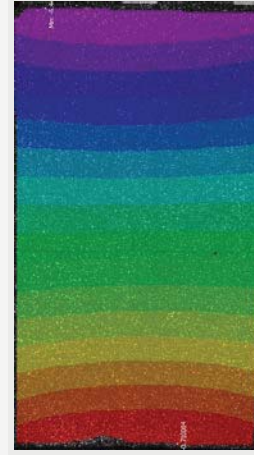


OML FEA Results

Buckling/ post buckling analysis results



Test correlation at buckling load of ~79.3 kips

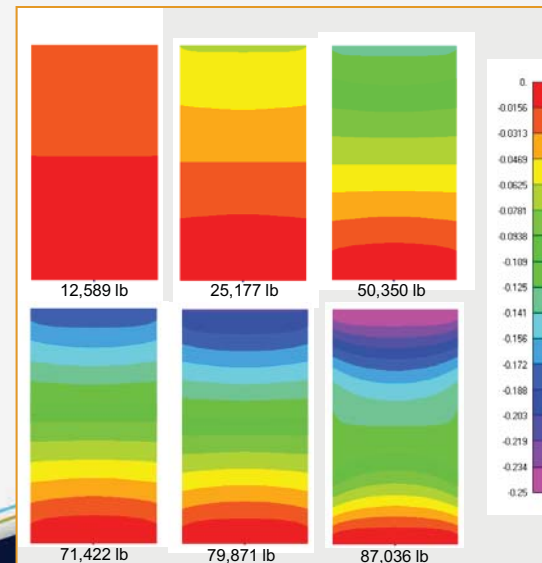


IML VIC Results



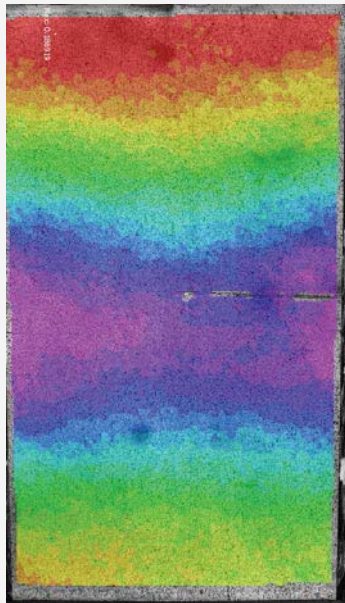
IML FEA Results

Buckling/ post buckling analysis results

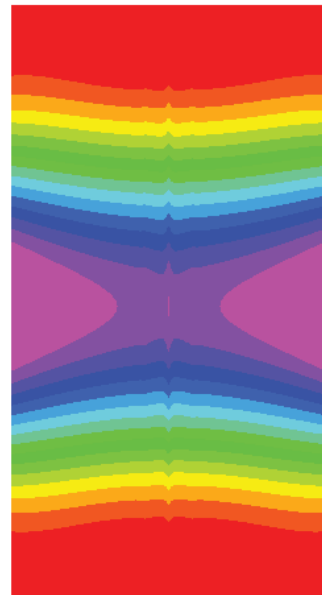


Out-of-plane Deformation Correlation

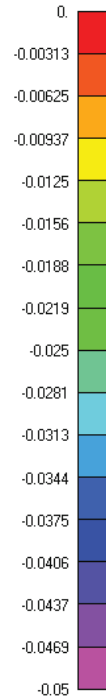
Test correlation at buckling load of ~79.3 kips



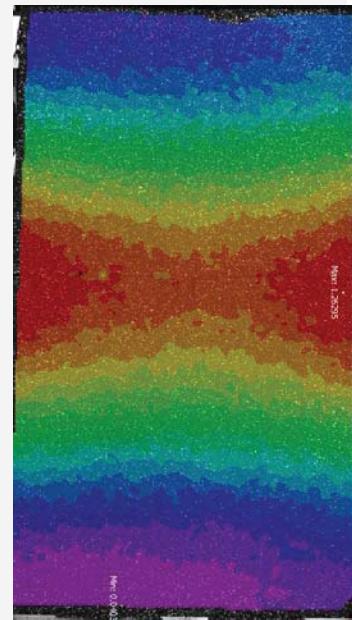
OML VIC Results



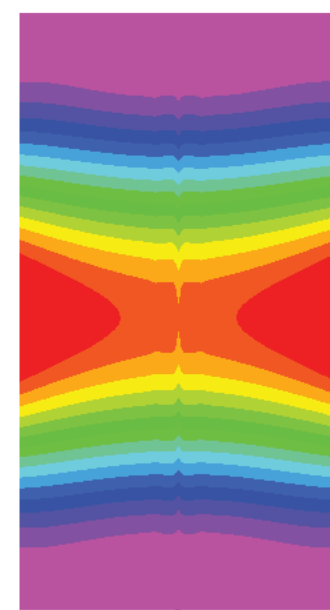
OML FEA Results



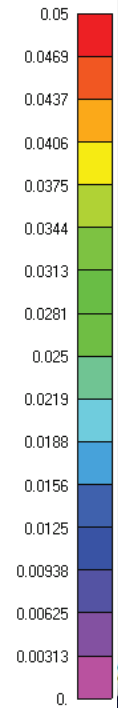
Test correlation at buckling load of ~79.3 kips



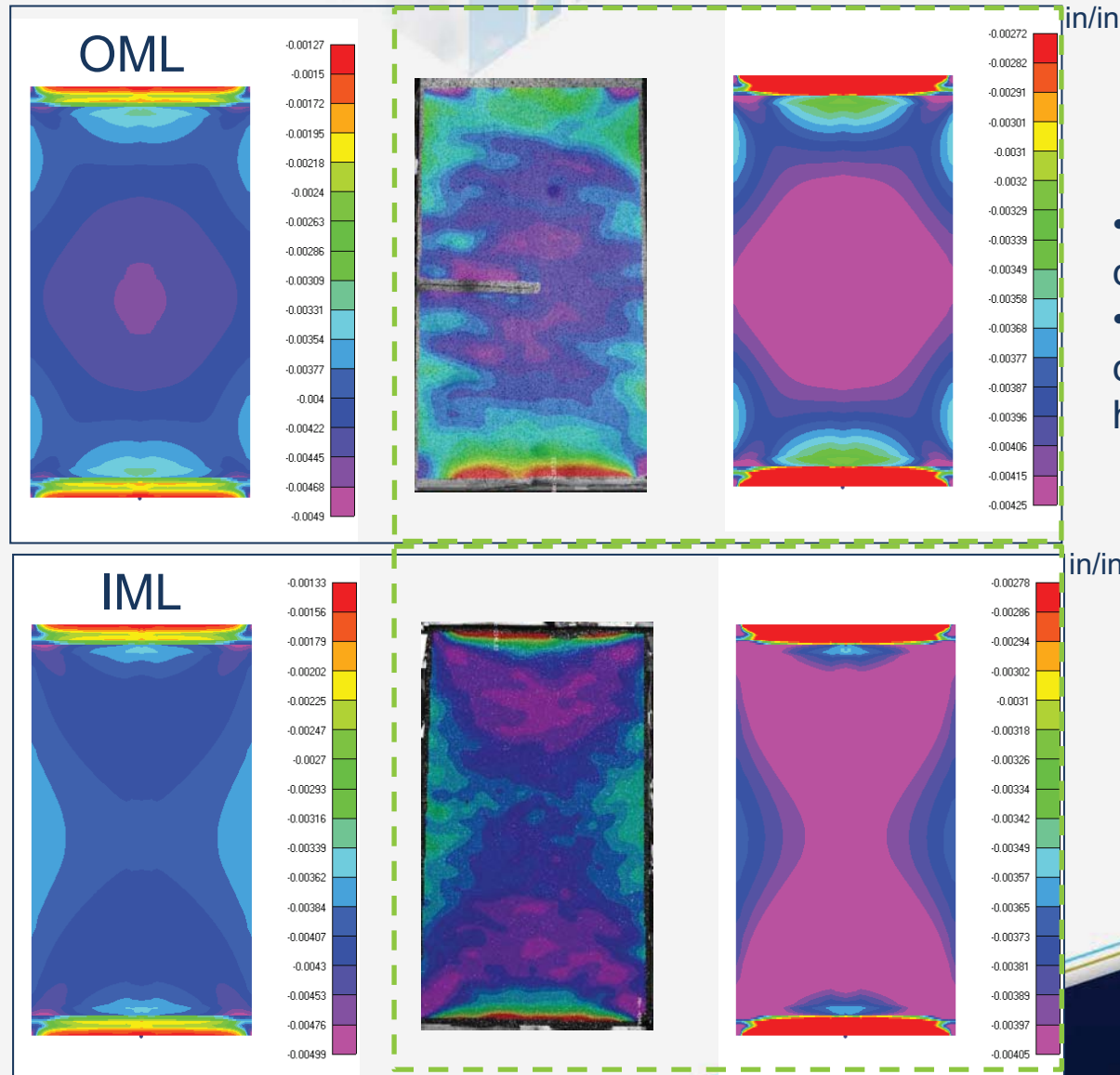
IML VIC Results



IML FEA Results



Axial Strain Correlation

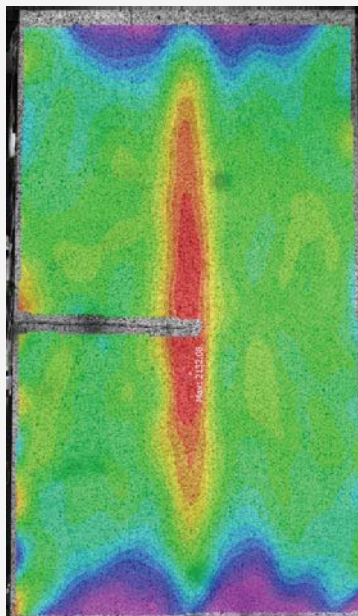


Test correlation at buckling load of ~79.3 kips

- Qualitative and qualitative comparison
- The ~4% stiffness difference causes the FEA to show slightly higher axial strains

Hoop Strain Correlation

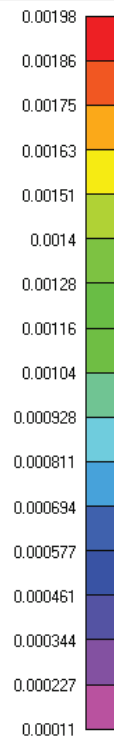
Test correlation at buckling load of ~79.3 kips



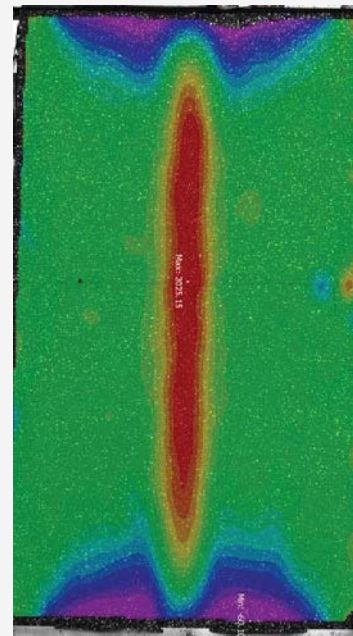
OML VIC Results



OML FEA Results



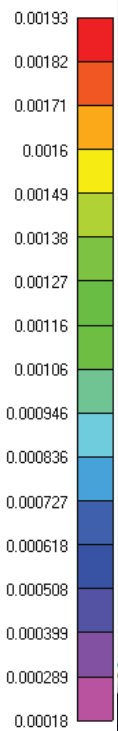
Test correlation at buckling load of ~79.3 kips



IML VIC Results

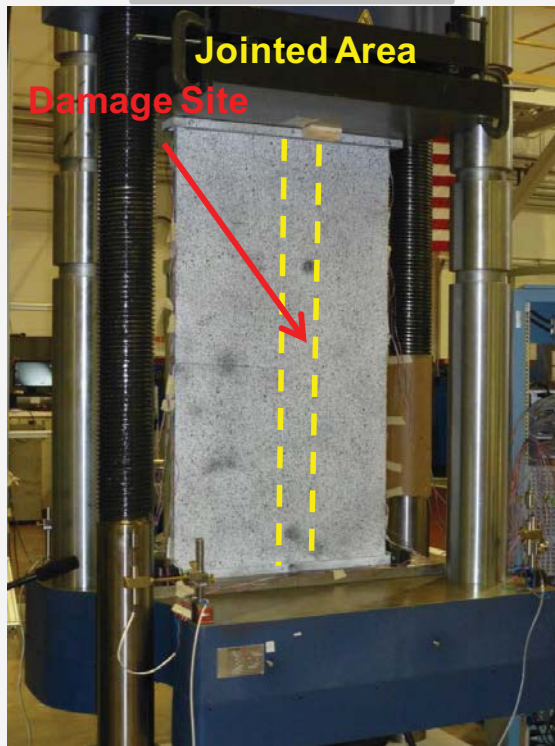


IML FEA Results

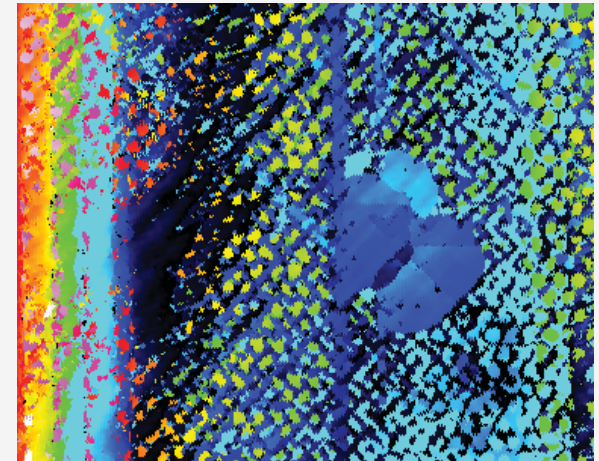


Damaged Jointed Panel Buckling Test Impacted OML – Off Joint Centerline

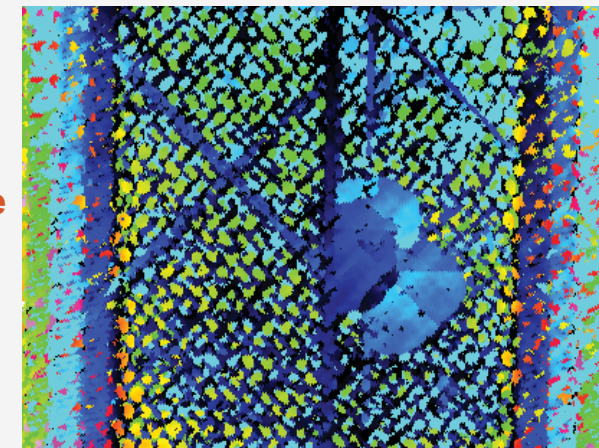
Buckling Test # 2



Pre-Test Impact Damage - UT Inspection Results



Post Test - UT Inspection Results of the Same Damage Area



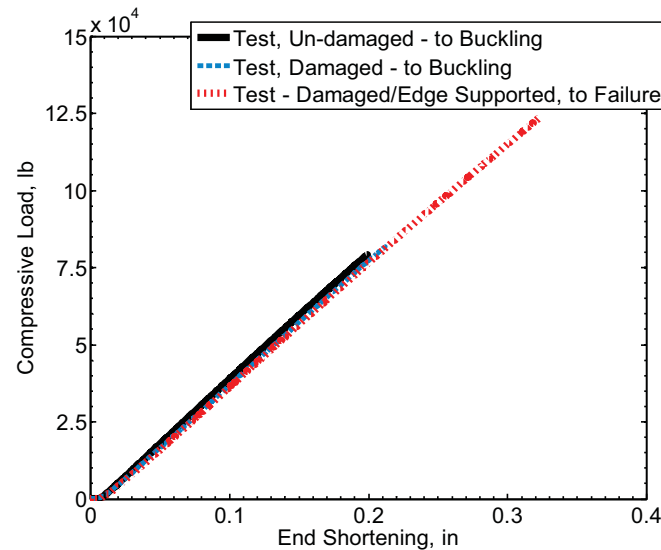
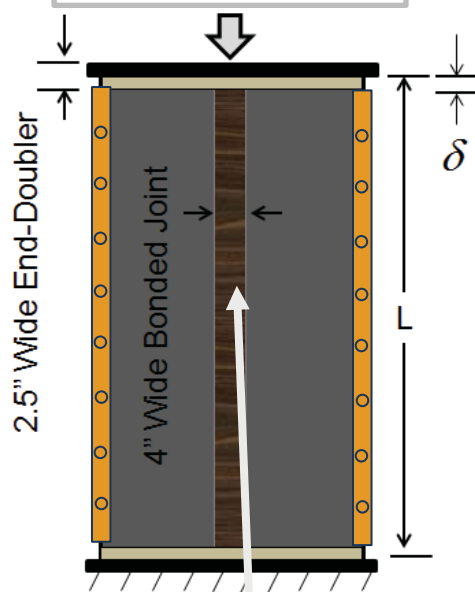
*Joint damage does not grow after buckling Test
(80K lbs-f)*

- 5.5 ft-lbs Impact Energy

Impact and UT inspections by W. Jackson & M. Czabaj at NASA/LaRC

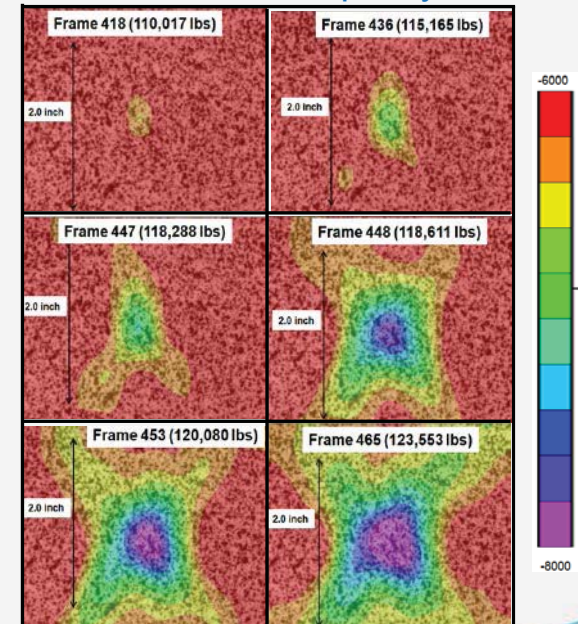
Edge-Supported Damaged Jointed Panel Tests: Impacted OML – Off Joint Centerline

Buckling Test # 3

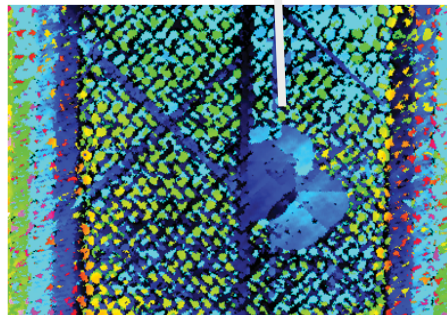


Objectives: To evaluate –

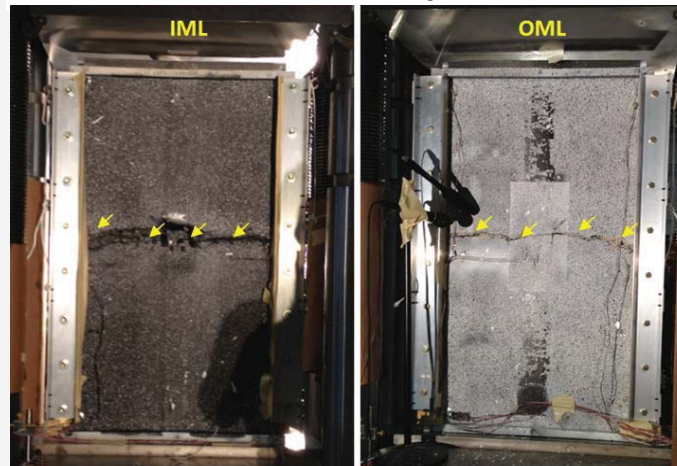
- Damage tolerance capability
- Ultimate strain capacity



The evolution of impacted damage with compressive load; the axial VIC strain at different loads/frames



Ultrasound NDE Result
After 5.5 ft-lb impact



The catastrophic failure at average center strain of $+6000 \mu\epsilon$ (~123 kips)



Next Steps

- Correlate the edge-supported panel compression test to failure
 - Modeling the impacted initial damage
 - Study the panel's response without and with the initial damage
 - And ultimately, model and analyze the damage propagation leading to the catastrophic failure at ~123 kips
 - **Objective:** To adapt a practical/general analysis approach for analyzing similar progressive failures in composite joints

Acknowledgement

- NASA's Composite for Exploration (CoEx) team who entrusted us to work for the advancement of joints technology and who performed the joints development with us:
 - *Harry Wilems* ([NASA/ Goddard Space Flight Center](#))
 - *Wade Jackson, Michael Czabaj, and Mark Shuart* ([NASA/Langley Research Center](#))
 - *Tom Krivanek, and James Sutter* ([NASA/ Glenn Research Center](#))
 - *Larry Pelham* ([NASA/Marshall Space Flight Center](#))

